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Localized surface plasmon-induced emission enhancement of a green light-emitting diode

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Abstract

The output enhancement of a green InGaN/GaN quantum-well (QW) light-emitting diode (LED) through the coupling of a QW with localized surface plasmons (LSPs), which are generated on Ag nanostructures on the top of the device, is demonstrated. The suitable Ag nanostructures for generating LSPs of resonance energies around the LED wavelength are formed by controlling the Ag deposition thickness and the post-thermal-annealing condition. With a 20 mA current injected onto the LED, enhancements of up to 150% in electroluminescence peak intensity and of 120% in integrated intensity are observed. By comparing this with a similar result for a blue LED previously published, it is confirmed that surface plasmon coupling for emission enhancement can be more effective for an InGaN/GaN QW of lower crystal quality, which normally corresponds to the emission of a longer wavelength.

1. Introduction

Although tremendous progress has been made in the fabrication techniques of InGaN/GaN quantum-well (QW) light-emitting diodes (LED) in the past decade, a significant improvement in its efficiency is still needed, particularly in the green–red range, for the applications of display and solid-state lighting. Among those methods for improving efficiency, the application of surface plasmon (SP) coupling with a QW for emission enhancement has recently caught much attention [1–9]. Basically, SPs, including surface plasmon polariton (SPP) and localized surface plasmon (LSP), represent behaviors of collective electron oscillation at a metal/dielectric interface. An SPP can propagate along the interface and an LSP describes local oscillation of an electron. Either kind of SP can effectively radiate into photons when momentum is matched. An SP extends an evanescent field into the dielectric. When a light emitter is located near the interface and covered by the evanescent field, it can exchange energy with SPs through the evanescent field. Via this coupling mechanism, the transfer of energy from the carriers in the coupled QW into SPs creates an effective light emission

channel. This emission channel is particularly effective when the defect density in the QW is high. Therefore, SP coupling with QWs has great potential for enhancing the emission efficiency of an InGaN/GaN QW LED, particularly in the green–red range. Recently, we have implemented a blue LED with an Ag/dielectric interface about 80 nm away from its single-InGaN/GaN QW on the p-GaN side. The designated SPP coupling effect enhances LED emission intensity by 25–50% [8].

However, based on our simulation study, LSP coupling can be more effective in emission enhancement when compared with SPP coupling because the latter has a higher dissipation rate around its resonance energy [10]. The SPP coupling for emission enhancement is less effective even though a metal grating structure is formed for momentum matching between the SPP and photon. Also, because usually a green-emitting InGaN/GaN QW has a higher defect density, SP coupling for emission enhancement is expected to be more effective when compared with a blue-emitting one. In this paper, we report the implementation of a yellowish green LED with its emission intensity enhanced by 90–220% via the coupling of its QW with LSPs, which are generated in Ag

Figure 1. Plan-view SEM images of four Ag structures on the LED epitaxial wafer, including (a) as-deposited thin film (TF) of 12 nm in thickness, (b) thermally annealed nanostructure of an 8 nm film, (c) thermally annealed nanostructure of a 10 nm film and (d) thermally annealed nanostructure of a 12 nm film.

nanostructures on the LED surface. The Ag nanostructures are formed through the thermal annealing of a thin Ag layer on the LED [11, 12]. By controlling the deposited Ag layer thickness and annealing conditions, Ag nanostructures of various sizes and shapes can be formed for inducing LSPs of different resonance energies.

2. Sample preparation and surface plasmon characterization

Three LED samples were prepared for comparison to demonstrate the emission enhancement through LSP–QW coupling. A single-InGaN/GaN QW LED epitaxial structure was grown with metal–organic chemical vapor deposition on the *c*-plane sapphire substrate. In this structure, after the growth of a 30 nm GaN buffer layer and a 3 μ m n-GaN layer, an InGaN/GaN QW of 3 nm in well thickness, 15 nm in bottom-barrier thickness and 10 nm in top-barrier thickness was deposited before the growth of a 10 nm p-Al_{0.2}Ga_{0.8}N layer and a 60 nm p-GaN layer. The room temperature photoluminescence (PL) spectral peak is located around 550 nm. The internal quantum efficiency of the grown QW is estimated to be 7%. In preparing the three LED samples, we followed the standard procedures to fabricate sample A, on which a periodic strip pattern of Ni (6 nm)/Au (6 nm) was coated on the mesa surface, except for the region of the p-contact pad, with the strip width at 10 μ m and spacing also at 10 μ m for current spreading.

To prepare suitable Ag nanostructures on the LED for effective coupling with the InGaN/GaN QW and, hence, effective emission enhancement, we tried several

Ag deposition thicknesses, but the same thermal annealing conditions. Figure 1 shows the plan-view scanning electron microscopy (SEM) images of four Ag structures on the LED epitaxial wafer, including (a) as-deposited thin film (TF) of 12 nm in thickness, (b) thermally annealed nanostructure of an 8 nm film, (c) thermally annealed nanostructure of a 10 nm film, and (d) thermally annealed nanostructure of a 12 nm film. Thermal annealing was performed at 200 °C for 40 min in ambient N₂. From the comparisons among figures 1(a)–(d), one can see that, after thermal annealing, the Ag thin film has been transformed into nanostructures. With a thicker deposited Ag thin film, the sizes of nano-island structures become larger and their shapes become more irregular. The size and shape determine the resonance energy of a generated LSP.

Figure 2 shows the transmission spectra of the four samples shown in figure 1. Here, one can see the monotonically decreasing trend with wavelength, except for a small dip around 425 nm, in the 12 nm Ag thin film (TF) sample. The dip around 425 nm is attributed to the SPP resonance generated at the plane interface between the Ag thin film and GaN. The transmission spectra of Ag thin films of smaller thicknesses are similar to this curve except that the general transmission level is higher. After thermal annealing, broad transmission dips are observed, indicating the absorption of LSPs generated on the Ag nanostructures (NS). Because of the large varieties of their size and shape, different LSP modes of different resonance energies lead to broad transmission dips in figure 2. Generally, smaller Ag nanostructures result in higher LSP resonance energies. As shown in figure 2, the wavelength corresponding to the transmission minimum redshifts as the Ag nanostructure becomes larger. Since the

Figure 2. Transmission spectra of various Ag structures in figure 1 showing SP resonance energies. The curves of TF (12 nm), NS (8 nm), NS (10 nm) and NS (12 nm) correspond to figures 1(a)–(d), respectively.

prepared LED epitaxial sample emits 550 nm light, the Ag nanostructures formed from 12 nm deposition are selected for LSP coupling with the InGaN/GaN QW in LED fabrication.

Based on the fabrication of LED sample A, as described above, in sample B, a 12 nm Ag thin film was deposited on the device top. Then, for preparing sample C, the LED was thermally annealed under the above-mentioned conditions to change the top Ag thin film into nanostructures in the window regions between the current spreading strips. Therefore, in samples B and C, the distance between the metal/semiconductor interface and the QW is around 80 nm. This distance is about the same as the e^{-1} decay length of the SPP evanescent field (70 nm) at wavelength 550 nm [13]. It is difficult to estimate the LSP evanescent field range because of the irregular shape of the Ag nanostructure. However, a range of the same order of magnitude as that of the SPP is expected. It is believed that the SPP dominates the SP–QW coupling in sample B while the LSP makes the major contribution in the QW coupling of sample C.

3. Emission enhancement of light-emitting diode

Figure 3 also shows the room temperature PL spectra of the three samples (the right ordinate). For reference, the transmission spectra of samples B and C (the left ordinate), which have already been shown as curves TF (12 nm) and NS (12 nm), respectively, in figure 2, are also plotted in figure 3. The PL measurement was excited by a 406 nm InGaN/GaN QW laser with the configuration of bottom (sapphire side) excitation and bottom PL recording. Here, one can see the PL suppression and enhancement in samples B and C, respectively, when compared with the standard LED sample (A). In sample B, the QW couples with the SPP such that the wavelength of the spectral center-of-mass is blueshifted from 553 nm in sample A to 551 nm. This blueshift is attributed to the stronger SPP coupling on the high-energy side of the PL spectrum because of the increasing SPP density of state as the photon energy becomes closer to the SPP resonance energy corresponding to 425 nm in wavelength. Because of the momentum mismatch between the SPP and photon and the high dissipation rate, PL is suppressed. On the other hand, in

Figure 3. Room temperature PL spectra (right ordinate) of the three LED samples showing their relative intensities. The transmission spectra (left ordinate) of LED samples B and C, corresponding to curves TF (12 nm) and NS (12 nm) in figure 2, respectively, are repeated here for reference.

Figure 4. EL spectra of the three LED samples showing their relative intensities when the injection current is 20 mA. The LED output was monitored from the polished bottom side.

sample C, the QW is coupled with LSPs induced on the metal nanostructures at the device top. Because an LSP mode has zero momentum and can match the momentum of the photon, it can radiate more effectively, leading to the PL enhancement shown in figure 3. Also, because the density of state of the LSP has a maximum around 594 nm, as signified by the minimum of the NS (12 nm) curve in figure 2, the stronger LSP coupling on the low-energy side of the PL spectrum in sample C leads to the redshift by 4 nm of its spectral center-of-mass with respect to that of sample A.

Figure 4 demonstrates the LED output spectra (electroluminescence—EL) showing their relative intensities at the injection current of 20 mA. The LED output was monitored from the polished bottom side. Here, one can first observe the emission enhancements in both samples B and C when compared with sample A. The higher EL intensity of sample B, compared with that of sample A, in figure 4 represents an opposite trend from that of PL intensity in figure 3. This difference disproves the possible attribution of the stronger intensity in sample B to the metal reflection at the device top. The spectral blueshift of sample B in figure 3 also supports the SPP coupling effect in this sample. The enhanced EL intensity of sample B in figure 4 is attributed to better current spreading after the coating of the 12 nm Ag layer. In

Figure 5. EL intensity variations of the three LED samples with injection current.

Figure 6. Current variations with applied voltage (I - V curves) of the three LED samples.

this situation, its spectral center-of-mass redshifts by 4 nm. In other words, although the SPP coupling in this sample leads to emission suppression, the more effective current spreading, when compared with sample A, still results in EL enhancement. In sample C, the LSP coupling results in quite effective emission, leading to 150% enhancement in peak intensity and 120% enhancement in integrated intensity at the injection current of 20 mA. LSPs have lower dissipation rates than SPPs. Also, LSPs on appropriate metal geometries can radiate more effectively [10]. With LSP coupling, the spectral center-of-mass in sample C redshifts by 5 nm from that in sample A. It is noted that the EL enhancement in sample C cannot be completely attributed to the improved current spreading effect because the isolated Ag nanostructure on this sample cannot significantly improve current spreading.

Figure 5 shows the output (EL) peak intensities of the three LED samples as functions of injection current. Here, one can again see the intensity enhancements of both samples B and C. With LSP coupling, sample C shows 90–220% output intensity enhancement over the conventional LED (sample A). Figure 6 shows the relations of current versus applied voltage (I - V curves) of the three samples. Here, one can see the smaller turn-on and 20 mA voltages in samples B and C when compared with sample A. These results are attributed to the improved current spreading effects after the Ag thin films are coated. After thermal annealing and the formation of Ag nanostructures, the current spreading effect is reduced and hence the device's electrical characteristic is degraded in sample C.

4. Conclusions

In summary, we have demonstrated the implementation of green LED output enhancement through the QW coupling with LSPs, which were generated on Ag nanostructures on the device. With 20 mA injection current, up to 150% EL peak intensity and 120% EL integrated intensity enhancements were observed. By comparing with the output results of sample B, we have also shown that SPP coupling is less effective in LED emission enhancement unless a scheme for matching the

momenta of SPP and photon is prepared. However, based on our previous numerical study [10], SPP coupling is still less effective for emission enhancement even though a metal grating structure is formed. Compared with the similar results of a blue LED published previously, we concluded that SP coupling for emission enhancement can be more effective for an InGaN/GaN QW of lower crystal quality, which normally corresponds to the emission of a longer wavelength.

Acknowledgments

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